



Surface fuel loadings within mulching treatments in Colorado coniferous forests

Mike A. Battaglia^{a,*}, Monique E. Rocca^b, Charles C. Rhoades^a, Michael G. Ryan^a

^a USDA Forest Service, Rocky Mountain Research Station, 240 West Prospect Rd, Fort Collins, CO 80526, USA

^b Colorado State University, Department of Forest, Rangeland, and Watershed Stewardship, Fort Collins, CO 80523, USA

ARTICLE INFO

Article history:

Received 17 March 2010

Received in revised form 28 July 2010

Accepted 5 August 2010

Keywords:

Mastication

Chipping

Fuels management

Fuel load equations

ABSTRACT

Recent large-scale, severe wildfires in the western United States have prompted extensive mechanical fuel treatment programs to reduce potential wildfire size and severity. Fuel reduction prescriptions typically target non-merchantable material so approaches to mechanically treat and distribute residue on site are becoming increasingly common. We examined how mulch treatments alter the distribution of woody material by size class by comparing paired mulched and untreated sites in lodgepole pine (*Pinus contorta*), mixed conifer, ponderosa pine (*Pinus ponderosa*), and pinyon pine/juniper (*Pinus edulis/Juniperus* sp.) forests 2–6 years after mechanical treatment. Mulching treatments reduced tree density and canopy bulk density, and increased canopy base height, potentially lowering active crown fire risk. In general, mulching increased total woody surface fuel loadings 2–3-fold, but the magnitude differed among forest types. Average total woody surface fuel loads in the untreated areas ranged between 7 and 12 Mg ha⁻¹, but increased to 27–63 Mg ha⁻¹ in treated areas. Large diameter fuels (>7.62 cm) represent about 35–69% of the total woody fuel load in the untreated areas, but only about 8–14% of the total fuel load in the treated areas. Woody fuels in treated areas were dominated by material <2.54 cm diameter (i.e. 1 and 10 h fuels). In general, mulch fuelbed depth was a useful predictor of fuel loading. Mulching created a compact fuelbed (i.e. bulk density 138–150 kg m⁻³) that differs from pretreatment needle-dominated fuelbed and will likely change fire behavior and effects. Quantification of the mulched fuelbed characteristics within these four forest types should aid in modification of current fuel models or creation of new fire behavior fuel models.

Published by Elsevier B.V.

1. Introduction

Recent large-scale, severe wildfires in the western United States have prompted the implementation of extensive fuel treatment programs aimed at reducing active crown fire behavior and potential wildfire size (USDA/DOI, 2008). Many of these fuel treatments are located within or near the wildland–urban interface, areas where human development borders or intermingles with forested lands of various ecosystems. As the human population grows, the wildland–urban interface expands (Radeloff et al., 2005; Theobald and Romme, 2007; Gude et al., 2008), and more area will require fuels management. Although many forested landscapes in the western U.S. were historically regulated by wildfire, opportunities to reintroduce fire using prescription burning to alter forest structure are limited by smoke restrictions and risk of fire escapes. Instead, mechanical treatments are a widely used method to reduce crown fire risk in the wildland–urban interface of the western United States (USDA/DOI, 2008).

To reduce crown fire risk, mechanical treatments often focus on reducing canopy fuels and interrupting the surface–canopy fuel continuum (Agee and Skinner, 2005). Since the small diameter trees, shrubs, and dead trees prescribed for removal are non-merchantable, managers are increasingly choosing the option to masticate or chip the material and leave it on site. Mastication treatments often use tracked machines with an attached vertical or horizontal shaft head mounted on an excavator boom or directly on the front of the vehicle (Harrod et al., 2009; Rummer, 2010). The masticator heads shred or grind the woody material into coarse, irregular pieces and the material can be hurled up to 30 m or more. Chipping treatments require felled trees and other material to be fed into a chipper. The resulting material is small, relatively uniform in size and scattered on the ground. These techniques (hereafter referred to as mulching) should reduce active crown fire risk by redistributing the canopy and ladder fuels and compacting them on the forest floor. Mulching treatments are being applied in a variety of forest types across the western U.S. (Hood and Wu, 2006; Kane et al., 2009; Owen et al., 2009; Reiner et al., 2009; Wolk and Rocca, 2009; Sharik et al., 2010), however, there is limited data on how these treatments alter surface fuel characteristics and in turn potential fire behavior.

The woody fuel generated from mulching treatments alters surface fuel loadings and fuel size distribution. The few studies that

* Corresponding author. Tel.: +1 970 498 1286; fax: +1 970 498 1212.

E-mail addresses: mbattaglia@fs.fed.us (M.A. Battaglia), rocca@warnernr.colostate.edu (M.E. Rocca), crhoades@fs.fed.us (C.C. Rhoades), mryan@fs.fed.us (M.G. Ryan).

Table 1

Site information for 18 mulched study sites located in Colorado and measured in 2007 or 2008.

Dominant tree species (>10 cm dbh)	Elevation (m)	Location	Treatment year
Lodgepole pine			
<i>Pinus contorta</i> (100%)	2800	USFS Arapaho and Roosevelt National Forest, Clear Creek Ranger District	2005
<i>Pinus contorta</i> (100%)	2690	USFS Arapaho and Roosevelt National Forest, Sulfur Ranger District	2001
<i>Pinus contorta</i> (98%)	2818	Golden Gate Canyon Park, Colorado State Park	2005
<i>Pinus contorta</i> (100%)	2657	YMCA Snow Mountain Ranch, Granby, Private	2003
<i>Pinus contorta</i> (96%)	2600	USFS Arapaho and Roosevelt National Forest, Boulder Ranger District	2003
Mixed conifer			
<i>Pinus flexilis</i> (44%), <i>Pinus ponderosa</i> (38%)	2900	Catamount Reservoir, Cascade (Private)	2005
<i>Pinus contorta</i> (58%), <i>Pinus ponderosa</i> (30%), <i>Pseudotsuga menziesii</i> (12%)	2760	USFS Arapaho and Roosevelt National Forest, Boulder Ranger District	2006
<i>Pinus contorta</i> (78%), <i>Pinus ponderosa</i> (9%), <i>Pseudotsuga menziesii</i> (12%)	2700	USFS Arapaho and Roosevelt National Forest, Boulder Ranger District	2006
Ponderosa pine			
<i>Pinus ponderosa</i> (58%), <i>Pseudotsuga menziesii</i> (42%)	2300	USFS, Pike National Forest, South Platte Ranger District	2004
<i>Pinus ponderosa</i> (50%), <i>Pseudotsuga menziesii</i> (50%)	2100	Lory State Park, Colorado State Park	2006
<i>Pinus ponderosa</i> (68%), <i>Pseudotsuga menziesii</i> (32%)	2130	Lower North Fork, Foxton, Private	2005
<i>Pinus ponderosa</i> (94%), <i>Pseudotsuga menziesii</i> (6%)	2360	USFS Pike National Forest, Pikes Peak Ranger District	2005
Pinyon pine/juniper			
<i>Pinus edulis</i> (89%), <i>Juniperus</i> sp. (10%)	2400	BLM, Salida	2006
<i>Pinus edulis</i> (65%), <i>Juniperus</i> sp. (35%)	2200	BLM, Montrose	2005
<i>Juniperus</i> sp. (84%), <i>Pinus edulis</i> (16%)	1915	BLM, Cortez	2004
<i>Juniperus</i> sp. (61%), <i>Pinus edulis</i> (39%)	2250	USFS San Juan National Forest, Dolores Ranger District	2005
<i>Juniperus</i> sp. (88%), <i>Pinus edulis</i> (12%)	2200	BLM, Kremmling	2006
<i>Juniperus</i> sp. (78%), <i>Pinus edulis</i> (22%)	2170	BLM, Cortez	2005

have estimated surface fuel loadings reported woody fuel loads in mulched treatments ranging from 16 to 65 Mg ha⁻¹ (Stephens and Moghaddas, 2005; Hood and Wu, 2006; Kane et al., 2009; Reiner et al., 2009). In most untreated forest types, 1000-h (coarse woody debris; >7.62 cm diameter) fuels comprise the greatest proportion of total fuel load (Brown and See, 1981; Battaglia et al., 2008; Huffman et al., 2009). In contrast, in mulch-treated areas of sites dominated by shrubs (Kane et al., 2009) or *Pinus edulis*/*Juniperus osteosperma* (Huffman et al., 2009), fuel loads were concentrated in the 1-h (<0.62 cm diameter) and 10-h (0.62–2.54 cm diameter) fuel size classes. Similar studies in other forest types, which have greater pretreatment densities and surface fuel biomass, may result in distinct mulch fuel size distributions.

Kane et al. (2009) demonstrated that mulched fuelbeds differ in loading by fuel particle size and fuelbed depth when compared to natural and slash-based fuelbeds. Mulched fuelbeds are often compacted, with fuelbed bulk densities exceeding 100 kg m⁻³ (Busse et al., 2005; Hood and Wu, 2006; Kane et al., 2009; Reiner et al., 2009), values that are more typical of duff than of woody fuelbeds (van Wagtenonk, 1998). Mixing of woody material during mulching also increases the mineral soil content of the fuelbed (Hood and Wu, 2006) owing to changes in fuelbed characteristics. Existing fire behavior fuel models are inadequate to estimate potential surface fire behavior and effects (Glitzenstein et al., 2006).

Development of fuel models to estimate fire behavior and fire effects in these novel treatments requires characterization of mulched fuelbeds. Mechanical mulching alters fuel particle shape and size and limits the utility of estimating fuel loadings with Brown's planar intercept method (Glitzenstein et al., 2006; Hood and Wu, 2006; Kane et al., 2009). Recent studies which compare Brown's planar intercept method (Brown, 1974; Brown et al., 1982) and other methods that use fuelbed depth and/or cover have shown differences in fuel load estimates (Glitzenstein et al., 2006; Hood and Wu, 2006; Kane et al., 2009), especially in the smaller fuel size classes (1-h and 10-h). Hood and Wu (2006) demonstrated that fuelbed depth was a good predictor of mulched fuel loads in *Pinus jeffreyi*–*Abies concolor* and *Pinus ponderosa*–*Quercus gambelii* forest types. Similar success was demonstrated in 25-year-old ponderosa pine plantations (Reiner et al., 2009) and in sites dominated by shrubs (Kane et al., 2009). Further studies are needed to

develop equations to predict fuel loads and fuel size distribution in mulched treatments of other forest types. Furthermore, equations that can predict mulch fuelbed loads and mulch depth based on the amount of tree biomass treated would aid managers in planning mulch treatments.

In this study, we established paired untreated/mulched sites within 4 coniferous forest types (i.e. lodgepole pine (*Pinus contorta*), mixed conifer, ponderosa pine (*P. ponderosa*), and pinyon pine/juniper (*P. edulis*/*Juniperus* sp.)) distributed across Colorado. The broad geographic scope of this study and replicated design is intended to better characterize differences in surface fuel loadings between untreated and mulched sites across multiple forest types. Specifically, our objectives were: (1) to quantify differences in ground cover, fuel loading, fuel size distribution, and mulch depth distribution between untreated and mulched areas; and (2) to develop equations that predict surface fuel loadings based on fuelbed depth, cover, and tree biomass treated.

2. Methods

2.1. Study sites and design

We measured the effects of mulching on forest floor cover and surface fuel loads at 18 sites across four forest types of the southern Rocky Mountains and the Colorado Plateau: lodgepole pine, mixed conifer (*P. ponderosa*, *Pseudotsuga menziesii*, *Pinus flexilis*, and *P. contorta*), ponderosa pine, and pinyon pine/juniper. These sites were distributed across a wide geographic range throughout Colorado and represent treatments across several federal, state, and other land agencies. The sites were mulched between 2001 and 2006 and fuels measured in 2007 or 2008 (Table 1). Mulch treatments were designed to reduce the risk of crown fire initiation and spread to alleviate threats to firefighters and homes, increase stand resilience to fire, reduce the number of dead and diseased trees, and recreate historic tree densities. Most stands were treated with a Hydroax® with a vertical shaft or rotary ax mower. Two of the stands (i.e. a lodgepole pine and a mixed conifer stand on the Arapaho and Roosevelt National Forest, Boulder Ranger District) were treated with a Morbark® chipper.

Five sites were located in lodgepole pine forests, with two sites on the western side of the continental divide and three sites on the eastern side. Lodgepole pine was the dominant (>95%) overstory tree species (Table 1). Three sites were established in the mixed conifer forests. This forest type lies between the lower elevations where ponderosa pine forests dominate and the upper elevations where lodgepole pine or subalpine species dominate. Tree species dominance was a mixture of lodgepole pine, limber pine, Douglas-fir, and ponderosa pine (Table 1). Four sites were established in the ponderosa pine forest type. Ponderosa pine was the dominant tree overstory species with various amounts of Douglas-fir (Table 1). Six sites were established in the pinyon pine/juniper woodland and they were distributed throughout central and western Colorado. Juniper species dominated four of the six sites (Table 1).

At each mulched study site, we identified an untreated reference area located within 1 km on sites with similar aspect and elevation to limit differences in soils and forest structure. Stump surveys in the mulched areas were used to verify similarities between untreated and mulched areas. In the summer of 2007 and 2008, we established three 50-m permanent transects in each of the treated and untreated areas of the 18 study sites. Transect orientation was selected using a randomly selected compass bearing.

2.2. Trees

Tree diameter, species, and status (live or dead) were measured along three 50-m belt transects. Transect width varied with treatment and tree size. Trees >10 cm diameter at breast height (dbh) were measured on a 20-m wide belt transect within the mulched areas and 10-m wide within the untreated areas. Trees <10 cm dbh (saplings) were measured on a 10-m belt transect within the mulched areas and a 4-m belt within the untreated areas. Saplings were tallied by dbh size (0–5 cm and 5–10 cm), status, and species. Stump diameters were measured in the mulched areas on belt transects 10-m in width for stumps >10 cm in diameter and 4-m in width for stumps <10 cm in diameter. When possible to identify with bark characteristics, species of tree stumps was recorded. Tree height, crown length, and crown width were measured on a subset of trees within each study area for tree biomass modeling purposes. Canopy bulk density and canopy base height were calculated using the Fire and Fuels extension to the Forest Vegetation Simulator (FFE-FVS) (Reinhardt and Crookston, 2003). FFE-FVS was also used to estimate the tree biomass cut and deposited on the ground.

2.3. Ground and herbaceous plant cover

Along each transect, 25 1-m² quadrats were established to measure ground cover and litter/duff depth. Ocular cover estimates were made for exposed rock, mineral soil, litter and duff, living woody material (exposed roots, stems, and tree boles including fresh stumps), and dead woody material. Dead woody material was separated into the three fuel particle sizes (1-h + 10-h = <2.54 cm diameter; 100-h = 2.55–7.6 cm diameter; 1000-h = >7.6 cm diameter). Size class classification was determined by the dimension with the narrowest diameter (Kane et al., 2009). Litter and duff depths were measured in five places in each quadrat at the center and at each corner. Litter was defined as fresh and partially decomposed organic forest debris located above the mineral soil, while duff consisted of highly decomposed organic matter below the litter layer and above mineral soil. In the mulched areas, it was difficult to distinguish litter, duff, and fine woody material (<10-h) layers due to the mixing of the forest floor caused by the equipment, so we combined our measurements of the depths of these components (litter + duff + fine woody debris).

2.4. Fuel loads

Destructive plot-based sampling was used to develop relationships between cover, depth and load of 1-h, 10-h, and 100-h woody fuels (Hood and Wu, 2006; Kane et al., 2009). Three 1-m² ‘calibration’ quadrats were established, 5-m offset from each transect at 10, 25, and 40 m. Cover estimates and depth measurements were the same as those conducted along the transect. Within untreated areas, all 1-h + 10-h and the 100-h woody fuels inside the 1-m² frame were collected. Litter and duff samples were collected from a 25 cm × 25 cm frame placed within the 1-m² quadrat. Within mulched areas, all of the 100-h woody fuels in quadrats were collected from the entire 1-m² quadrat. The mulch mixture of litter, duff, and 1-h + 10-h fuels in quadrats within the mulched areas was collected from a 25 cm × 25 cm frame placed within the 1-m² quadrat. The total mulch depth was also measured within the smaller frame. Once the fuel was collected, the wet weight of each fuel type was weighed, bagged, and brought back to the lab. Due to logistics and space, only a ~200 g subsample of the 100-h fuels from each quadrat was brought back to the lab. All fuels were oven-dried to a constant dry mass at 60 °C in a drying oven to convert wet weight to dry weight. Bulk density of each litter and duff sample from the untreated areas within each forest type (lodgepole: litter = 73.2 kg m⁻³ and duff = 95.2 kg m⁻³; mixed conifer: litter = 46.6 kg m⁻³ and duff = 64.2 kg m⁻³; ponderosa pine: litter = 53.6 kg m⁻³ and duff = 64.2 kg m⁻³; pinyon pine/juniper: litter = 55.4 kg m⁻³ and duff = 89.5 kg m⁻³) were calculated and used to estimate litter and duff mass. Mulch bulk density (kg m⁻³) for the mulch mixture was calculated by dividing the total fuel load estimates of (1-h + 10-h + litter + duff) per area by the total mulch depth (m). Once mulch bulk density was calculated, the mulch mixture was separated by fuel size class (1-h, 10-h, litter/duff) and each fuel component was reweighed to determine its proportion of the total weight. The 1-h and 10-h fuels collected from the untreated areas were also separated and reweighed to calculate proportions.

Woody fuels >7.62 cm (1000-h) fuel loadings were measured along a 4 m × 50 m belt transect. The length, diameter at each end, and the decomposition class of each log encountered was recorded (Bate et al., 2004). The volume of the 1000-h fuels was calculated as a frustum of a paraboloid (Harmon and Sexton, 1996; Bate et al., 2004) with specific gravity of sound (0.4) and rotten (0.3) wood (Brown and See, 1981).

Herbaceous fine fuel loads were measured on the calibration quadrats. Ocular estimates of herbaceous cover (aerial coverage for live plants) at the peak of the growing season (i.e. late July to August) were estimated for all graminoids and forbs rooted inside the 1-m² quadrats. The herbaceous material was clipped within 1 cm of the surface and placed in a bag, oven dried at 60 °C for 48 h, and weighted to the nearest tenth of a gram.

2.5. Data analysis

All statistical analyses were performed using SAS v 9.2 (SAS, 2008). For each forest type and treatment, linear regression analysis was used to determine the relationship between surface fuel loadings and a predictor variable (fuelbed depth or %cover) from the destructive plot-based sampling estimates. Because we were interested in developing an easy metric for predicting mulch fuel loads, we did not explore a depth × cover relationship; a metric that would take considerable time to estimate for managers. In effect, our measurements of depth already account for cover, since we averaged 5 depth measurements distributed spatially within the square meter. Fuelbed depth was used to predict total mulch fuelbed load (litter + duff + 1-h + 10-h). Percent cover of 1-h + 10-h was used to predict 1-h + 10-h fuel load in untreated areas. Separate equations were developed to predict 100-h fuel loads for the

Table 2
Mean (and standard error) stand and canopy fuel characteristics. BA: basal area, TPH: trees per hectare, QMD: quadratic mean diameter, CBH: canopy base height, and CBD: canopy bulk density. Mean values in a row within a forest type followed by different letters are significantly different ($P < 0.05$).

	Lodgepole pine		Mixed conifer		Ponderosa pine		Pinyon pine/juniper	
	Untreated	Mulched	Untreated	Mulched	Untreated	Mulched	Untreated	Mulched
BA >10 cm dbh	35.3 a (3.3)	10.2 b (2.1)	36.6 a (4.3)	4.2 b (2.5)	24.3 a (3.7)	11.0 b (2.5)	20.4 a (4.3)	11.4 b (4.5)
BA <10 cm dbh	3.5 a (0.9)	0.3 b (0.2)	1.9 (0.5)	0.9 (0.6)	2.6 a (1.0)	0.15 b (0.1)	1.7 a (0.3)	0.4 b (0.2)
TPH >10 cm dbh	1691 a (132)	383 b (89)	1118 a (264)	55 b (28)	659 a (125)	180 b (79)	580 a (116)	203 b (54)
TPH <10 cm dbh	1107 a (216)	89 b (54)	776 (211)	291 (184)	1598 a (495)	69 b (59)	671 a (118)	193 b (75)
QMD (cm)	5.7 a (0.3)	6.9 b (0.4)	7.0 a (0.5)	11.9 b (0.8)	6.0 a (0.9)	11.4 b (1.4)	6.2 (0.6)	7.9 (1.2)
CBH (m)	5.8 a (1.4)	7.7 b (1.1)	2.5 a (0.4)	5.1 b (0.6)	2.3 (0.7)	5.4 (1.1)	3.3 (0.6)	3.9 (0.8)
CBD (kg m ⁻³)	0.15 a (0.03)	0.04 b (0.01)	0.14 a (0.01)	0.01 b (0.009)	0.12 a (0.02)	0.04 b (0.01)	0.02 (0.006)	0.007 (0.002)

treated and untreated areas, but both used percent cover of 100-h fuels as the predictor variable. All linear regressions were tested for linearity, normality, and homoscedasticity.

We used the equations developed from the destructive plot-based sampling to estimate fuel loads for each transect. The estimated mulch fuelbed load was broken down further into its separate components based on the proportion that each fuel category contributed to the total mulch fuelbed load determined from the sorting of material from the destructive plot-based sampling. We also calculated the proportion that each woody fuel component contributed to the total woody surface fuel load for the untreated and treated areas for each forest type. To determine changes in fuelbed properties, the ratio of needle litter loading to 1-h fuel loading was also calculated for untreated and treated areas for each forest type. Principle Components Analyses (PCAs) served to visualize the relationships between the different fuel components (litter, duff, dead wood by size class, and live fuels) and how they differed across treatments and forest types. For these analyses, plots were considered individually regardless of site.

Once fuel loads were calculated, linear regression analysis was used to determine the relationship between tree biomass cut (estimated with FVS) and the sum of litter and woody surface fuels in mulched areas. To aid in predicting the potential average mulch depth that could be deposited, a relationship between tree biomass cut and total fuelbed load was also determined.

For each forest type, a mixed-model ANOVA was used to detect treatment differences for each substrate cover, fuel loading category, and needle litter: 1-h fuel load ratio. Site and site \times treatment were designated as random variables and treatment as a fixed variable. Data that did not meet assumptions of equal variances or normality were log transformed. Differences among treatments were considered statistically significant when $P \leq 0.05$. Mixed effects ANOVAs were performed using PROC GLIMMIX. Proc FREQ and Proc SUMMARY were used to characterize mulch fuelbed depth distribution and median fuelbed depth for each forest type, respectively.

We tested for differences of surface fuel loads in mulched areas among forest types, using a multi-response permutation procedure (MRPP) based on a Euclidian distance metric. All pairs of forest types were compared using a Bonferroni-corrected $\alpha = 0.008$.

Bootstrap analysis was used to determine the number of fuelbed depth measurements that were required to minimize variability within each forest type. Bootstrap analysis statistically increases sample size by randomly sampling points from the original dataset. We used standard, with-replacement bootstrapping technique to create 2000 observations at each sample size tested (3–25). The

recommended sample size was determined to be at the point where an increase in sample size did not have a big impact on the estimate of the standard deviation (Sikkink and Keane, 2008; Kane et al., 2009).

3. Results

3.1. Changes in forest structure

Mulching treatments reduced tree basal area and trees per hectare in each forest type compared to the untreated control (Table 2). Total tree basal area in the mulched treatments ranged between 4 and 11 m² ha⁻¹, 47–89% lower than the untreated controls. Lodgepole pine and mixed conifer had the greatest absolute reduction in basal area, followed by ponderosa pine and pinyon pine/juniper. Total tree density was 69–97% lower in the mulched treatments, with low densities of standing dead material.

Mulching significantly increased the quadratic mean diameter and canopy base height of the residual stands, and significantly reduced canopy bulk density of all forest types except pinyon pine/juniper (Table 2).

3.2. Ground cover

Mulching treatments altered the substrate covering the forest floor. In untreated stands, litter and duff cover were dominant in all the forest types; woody fuel cover rarely exceeded 10% (Fig. 1). In untreated ponderosa pine, mixed conifer, and lodgepole pine stands, litter/duff cover ranged from 76 to 87%. However, mulching significantly decreased litter/duff cover to 30–45% (Fig. 1a–c). The decrease in litter/duff coverage was in part due to the significant increase in coverage of 1-h and 10-h fuel sized particles, which covered 30–52% of the forest floor (Fig. 1a–c). The addition of the 1-h and 10-h fuels mixed with and buried the forest floor. In untreated pinyon pine/juniper stands ground cover was a mixture of litter/duff (45%) and bare soil (32%). In the mulched stands, the addition of 1-h and 10-h fuels significantly decreased both litter/duff (35%) and bare soil (24%) cover (Fig. 1d).

The changes in cover of 100-h and 1000-h fuels varied among forest types. In lodgepole pine and ponderosa pine stands, 100-h fuel cover significantly increased (Fig. 1a and c), but the change in coverage was not significant for the mixed conifer or pinyon pine/juniper stands (Fig. 1b and d). Although the cover in smaller fuel size classes increased, mulching treatments did not change the cover of 1000-h fuels in any of the forest types (Fig. 1).

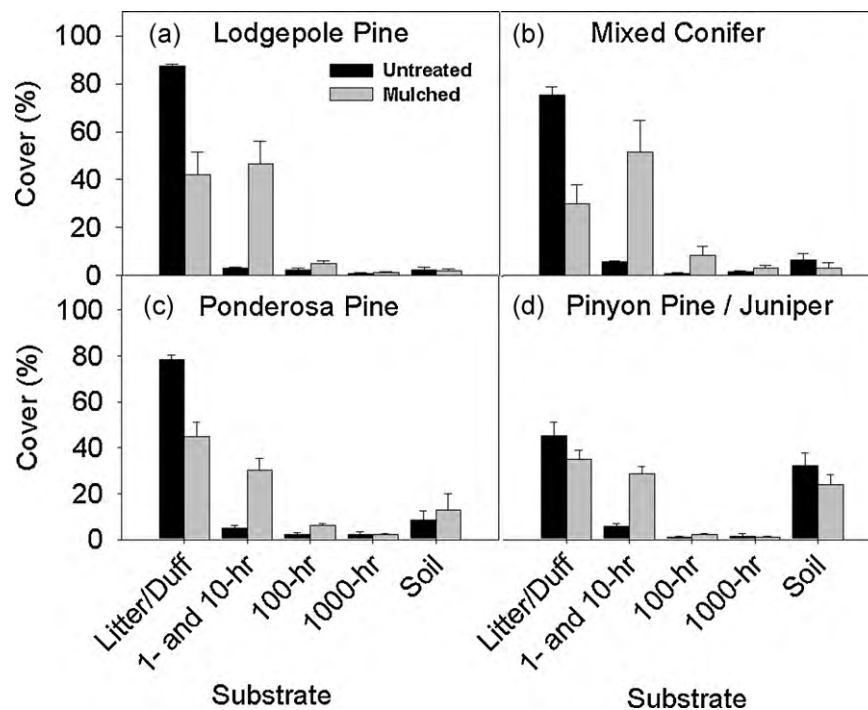


Fig. 1. Mean cover (and standard error) of forest floor substrate variables in untreated and mulched lodgepole pine, mixed conifer, ponderosa pine, and pinyon pine/juniper stands.

3.3. Estimating fuel loads

Fuelbed depth was a useful predictor to estimate mulch fuelbed loadings (Table 3), which consisted of a mixture of litter, duff, 1-h, and 10-h fuels. Fuelbed depth explained 84–90% of the variability in mulch fuelbed loadings in lodgepole pine, ponderosa pine, and pinyon pine/juniper stands, but only 58% in mixed conifer stands.

We also developed a relationship of depth and mulch fuelbed loadings for all forest types combined. Although the relationship of all forest types combined had a slightly lower r^2 than three of the four individual forest types, the slope was similar to the individual equations. Bootstrap analysis indicated that the optimal sampling intensity to estimate mulch fuelbed loadings is about 10 samples for a 50-m transect, regardless of forest type (Fig. 2).

Table 3

Linear regression results between fuelbed depth (cm) or fuel cover (%) and litter/woody mulch fuelbed load (kg m^{-2}) across mulched sites in four forest types in Colorado. Linear regression form: $y = b_0 + b_1(x)$. Mulch fuelbed = litter + duff + 1-h + 10-h fuels. All equations were significant ($P < 0.001$).

Fuel type	Treatment	b_0	b_1	Predictor variable	r^2	n	RMSE
Lodgepole pine							
Mulch fuelbed ^a	Mulched	−0.3858	1.5038	Depth (cm)	0.84	49	2.3
100-h	Mulched	0.0385	0.0927	% cover 100-h	0.75	39	0.316
1-h + 10-h	Untreated	0.0579	0.0410	% cover 1-h + 10-h	0.56	41	0.123
100-h	Untreated	−0.0499	0.1663	% cover 100-h	0.94	42	0.198
Mixed conifer							
Mulch fuelbed ^a	Mulched	−1.667	1.8076	Depth (cm)	0.58	26	3.34
100-h	Mulched	0.0892	0.115	% cover 100-h	0.81	26	0.36
1-h + 10-h	Untreated	0.0234	0.0207	% cover 1-h + 10-h	0.41	27	0.057
100-h	Untreated	−0.0026	0.1005	% cover 100-h	0.84	25	0.04
Ponderosa pine							
Mulch fuelbed ^a	Mulched	−0.2559	1.4315	Depth (cm)	0.86	35	1.8
100-h	Mulched	0.0367	0.1144	% cover 100-h	0.76	36	0.315
1-h + 10h	Untreated	−0.0004	0.0323	% cover 1-h + 10-h	0.78	34	0.051
100-h	Untreated	−0.0159	0.1156	% cover 100-h	0.93	35	0.07
Pinyon pine/juniper							
Mulch fuelbed ^a	Mulched	−0.1050	1.5904	Depth (cm)	0.90	27	1.48
100-h	Mulched	0.1097	0.1395	% cover 100-h	0.82	53	0.32
1-h + 10-h	Untreated	0.0711	0.0245	% cover 1-h + 10-h	0.37	49	0.124
100-h	Untreated	0.0005	0.1116	% cover 100-h	0.97	48	0.014
All ecosystems							
Mulch fuelbed ^a	Mulched	−0.2030	1.5287	Depth (cm)	0.71	137	2.89

Lodgepole pine: litter = 0.18; duff = 0.20; 1-h = 0.29, 10-h = 0.33.

Mixed conifer: litter = 0.29; duff = 0.20; 1-h = 0.25, 10-h = 0.26.

Ponderosa pine/Douglas-fir: litter = 0.27; duff = 0.21; 1-h = 0.16, 10-h = 0.36.

Pinyon pine/juniper: litter = 0.26; duff = 0.15; 1-h = 0.23, 10-h = 0.36.

^a To break down the fuel loads into litter, duff, 1 h and 10 h fuel size classes apply these proportions to the predicted estimates of mulch fuelbed load (kg m^{-2}).

Table 4
Linear regression results for total fuels (Mg ha^{-1}) or litter/woody mulch fuelbed load (Mg ha^{-1}) based on tree biomass treated. Tree biomass treated estimated using the Forest Vegetation Simulator. Linear regression form: $y = b_0 + b_1(x)$. Mulch fuelbed = litter + duff + 1-h + 10-h fuels. All equations were significant ($P < 0.001$).

Fuel type	Treatment	b_0	b_1	Predictor variable	r^2	n	RMSE
Total fuels (Mg ha^{-1})	Mulched	-2.811	0.967	Tree biomass treated (Mg ha^{-1})	0.76	18	10.97
Mulch fuelbed ^a	Mulched	1.072	0.795	Tree biomass treated (Mg ha^{-1})	0.67	18	1.12

Mixed conifer: litter = 0.29; duff = 0.20; 1-h = 0.25, 10-h = 0.26.

Ponderosa pine/Douglas-fir: litter = 0.27; duff = 0.21; 1-h = 0.16, 10-h = 0.36.

Pinyon pine/juniper: litter = 0.26; duff = 0.15; 1-h = 0.23, 10-h = 0.36.

Lodgepole pine: litter = 0.18; duff = 0.20; 1-h = 0.29, 10-h = 0.33.

^a To break down the fuel loads into litter, duff, 1 h and 10 h fuel size classes apply these proportions to the predicted estimates of mulch fuelbed load (Mg ha^{-1}).

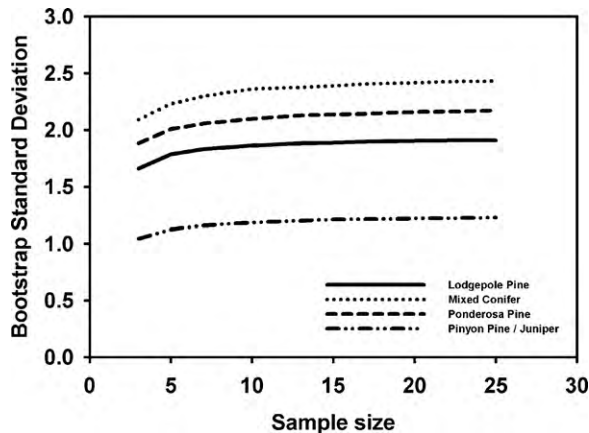


Fig. 2. Effect of sample size on the bootstrap standard deviation of each sample mean (2000 iterations) for forest floor depth (variable used to estimate mulch fuelbed load) in each forest type.

Cover was a useful predictor to estimate 100-h fuel loadings in mulched treatment (Table 3). To be consistent, we chose to measure untreated fuel loads using the same methodology (% cover-fuel load) as we used in the mulched areas. Separate equations were developed for the untreated fuels because the fuel particle sizes and shapes were not the same as those for mulched fuels. Our ability to predict 1-h and 10-h fuel loads based on %cover varied (Table 3). Pinyon pine/juniper, mixed conifer, and lodgepole pine forest types showed moderately good relationships with r^2 values ranging from 0.37 to 0.56. Ponderosa pine had a stronger relationship, with a r^2 value of 0.78 (Table 3). Percent cover of 100-h fuels in untreated areas was a good predictor in untreated areas (r^2 values ranged between 0.84 and 0.97).

The amount of tree biomass treated with the mastication equipment was a good predictor of the total amount of needle litter and woody material deposited on the forest floor (Table 4). The

amount of tree biomass treated was also a fairly good predictor of the amount of mulch (i.e. litter + duff + 1 hr + 10 hr) that was present on the forest floor (Table 4). For example, if an untreated ponderosa pine stands has 50 Mg ha^{-1} of tree biomass, 40.8 Mg ha^{-1} of mulch (litter, duff, 1-h and 10-h sized fuels) would be found on the forest floor (Table 5).

3.4. Fuel loads and fuelbed characteristics

Mulching substantially increased surface fuel loads in all of the forest types (Table 6). However, the magnitude of the total increase differed among the forests (mixed conifer > lodgepole pine > ponderosa pine > pinyon-juniper). Average total woody fuel loads in the untreated areas ranged between 7 and 12 Mg ha^{-1} and mulched areas ranged between 27 and 63 Mg ha^{-1} (Table 6). Large diameter fuels (>7.62 cm; 1000-h) represented about 35–69% of the total woody fuel load in the untreated areas, but only 8–14% in the mulched areas (Fig. 3). The majority of woody fuels in mulched areas were 1-h and 10-h fuels (<2.54 cm in diameter), composing between 67 and 78% of total woody fuel loadings (Fig. 3). Needle litter mass increased significantly in the mulched areas of the mixed conifer, ponderosa pine, and pinyon pine/juniper, but not in the lodgepole pine forest types (Table 6). Average herbaceous fuel loads increased significantly in the ponderosa pine and pinyon pine/juniper, but did not significantly increase in the lodgepole pine or mixed conifer stands (Table 6). Multivariate analysis of fuelbeds indicated that mulched plots separated from untreated plots along two PCA axes, which together explained 42% of the original variance in the fuels data (Fig. 4). Axis 1 correlated negatively with litter and the 1, 10, and 100 h fuel loads, while Axis 2 correlated positively with duff and coarse woody debris and negatively with live fuels.

Median fuelbed bulk densities in mulched areas were approximately 137 kg m^{-3} for lodgepole pine, mixed conifer, and ponderosa pine and 150 kg m^{-3} for pinyon pine/juniper. The increased surface woody fuel component in mulched areas corresponds to a shift from a needle fuelbed to a compact woody/needle

Table 5
Estimated average depth of mulch based on tree biomass treated in for lodgepole pine, mixed conifer, ponderosa pine, and pinyon pine/juniper forests of Colorado. Average mulch fuelbed depth = mulch fuelbed mass/mulch fuelbed bulk density.

Tree biomass treated ^a (Mg ha^{-1})	Mulch fuelbed mass (litter + duff + 1-h + 10-h) (Mg ha^{-1})	Pinyon pine/juniper Approximate average mulch depth (cm)	Lodgepole pine, mixed conifer, and ponderosa pine Approximate average mulch depth (cm)
10	9.0	0.6	0.7
25	20.9	1.4	1.5
50	40.8	2.7	3.0
75	60.7	4.1	4.4
100	80.6	5.4	5.8
125	100.5	6.7	7.3

Lodgepole pine: maximum: 71–98; treated: 25–40.

Mixed conifer: maximum: 50–80; treated: 36–49.

Ponderosa pine: maximum: 51–82; treated: 25–41.

Pinyon pine/juniper: maximum: 27–141; treated: 14–71.

^a Range of maximum standing tree biomass and treated biomass for each forest type.

Table 6

Mean (and standard error) fuel loads (Mg ha^{-1}) for untreated and mulched areas (surface by timelag fuel moisture class, ground, and herbaceous) of four coniferous forest types in Colorado.

	Lodgepole pine		Mixed conifer		Ponderosa pine		Pinyon pine/juniper	
	Untreated	Mulched	Untreated	Mulched	Untreated	Mulched	Untreated	Mulched
Litter	12.0 (1.4)	10.2 (1.2)	13.2 a (0.37)	27.7 b (0.39)	10.5 a (2.9)	13.6 b (2.6)	6.0 a (1.1)	8.6 b (1.6)
Duff	14.2 (3.4)	11.5 (2.2)	12.8 (3.2)	19.15 (4.6)	8.7 (4.0)	10.5 (2.2)	4.2 (1.5)	4.9 (2.2)
1-h	1.04 a (0.22)	16.9 b (5.9)	0.64 a (0.04)	23.03 b (8.79)	0.54 a (0.15)	8.0 b (1.9)	1.08 a (0.17)	7.81 b (2.2)
10-h	0.83 a (0.04)	19.3 b (2.6)	0.80 a (0.09)	24.5 b (5.7)	0.72 a (0.20)	18.02 b (3.3)	1.09 a (0.21)	12.0 b (2.5)
100-h	3.5 (1.3)	5.2 (0.9)	1.07 (0.25)	10.8 (4.1)	2.45 a (1.04)	7.4 b (1.0)	1.02 a (0.50)	4.15 b (0.6)
1000-h	2.9 (0.65)	5.32 (2.02)	4.93 (1.47)	5.03 (2.25)	8.29 (3.49)	5.27 (0.67)	4.15 (2.2)	3.18 (1.24)
Total woody	8.3 a (1.5)	46.7 b (8.6)	7.43 a (1.7)	63.4 b (12.2)	12.0 a (4.7)	38.7 b (5.0)	7.3 a (2.8)	27.2 b (3.6)
Herbaceous	0.08 (0.05)	0.16 (0.06)	0.06 (0.02)	0.11 (0.05)	0.11 a (0.03)	0.23 b (0.10)	0.26 a (0.08)	0.39 b (0.07)

Mean values in a row within an ecosystem followed by different letters are significantly different ($P < 0.05$).

Table 7

Ratio of needle litter fuel loads to 1 h fuel loads. Ratios were significantly different ($P < 0.0002$) between untreated and mulched areas for lodgepole pine, mixed conifer, ponderosa pine, and pinyon pine.

Forest type	Untreated	Mulched
Lodgepole pine	11.5	0.6
Mixed conifer	20.6	1.2
Ponderosa pine	19.4	1.7
Pinyon pine/juniper	5.6	1.2

fuelbed as indicated by the ratio of needle litter fuel load to 1-h fuel loads (Table 7).

When mulched plots were considered alone, fuel loads differed among forest types ($p < 0.0001$, MRPP). All pairs of forest types were significantly different from the others ($p < 0.001$), except for lodgepole pine and ponderosa pine, which could not be distinguished

statistically ($p = 0.07$). The various fuel components in mulched plots were highly intercorrelated along a single axis of variability, resulting in a one-dimensional PCA (not shown). This suggests that the mulched fuel beds differ only in their total fuel load, and that the proportions of total fuel in each category remain relatively constant across plots. MRPP and PCA analyses based on the proportions of the total fuel load that falls in each category confirms this (not shown).

Mulch depth distribution varied across ecosystems (Fig. 5). Mulch depth in the pinyon pine/juniper stands ranged between 0 and 9 cm (Fig. 5d) with a median depth of 1.4 cm. Both lodgepole pine and ponderosa pine stands had mulch depths that ranged between 0 and 13 cm (Fig. 5a and c), with median mulch depths of 3.8 and 3.3 cm, respectively. Mixed conifer stands had the deepest mulch. Mulch depths ranged from 0.5 to 15 cm, with a median mulch depth of 6.0 cm (Fig. 5b).

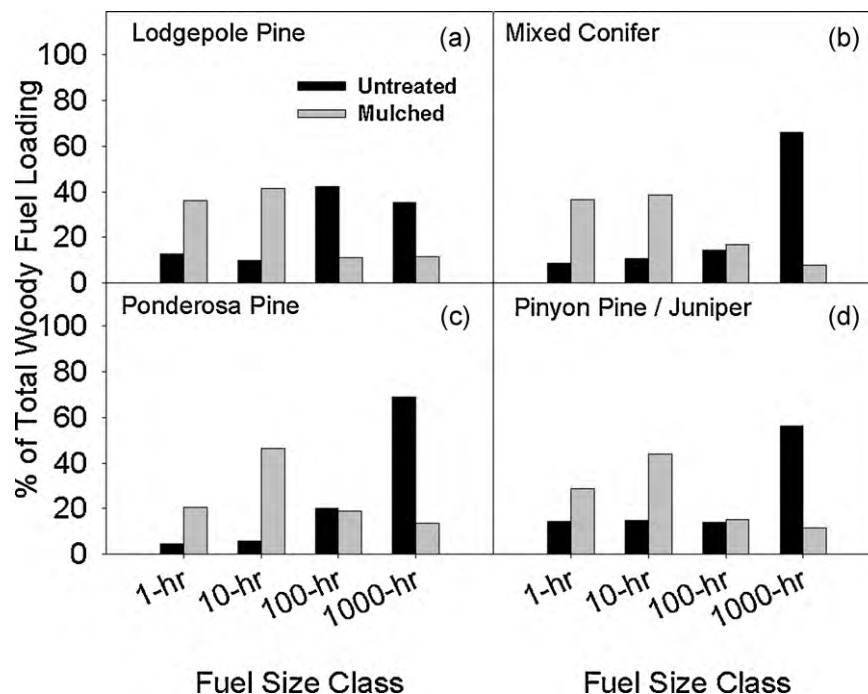


Fig. 3. Percentage that each fuel size class contributes to the total woody fuel load in untreated and mulched study areas in lodgepole pine, mixed conifer, ponderosa pine, and pinyon pine/juniper.

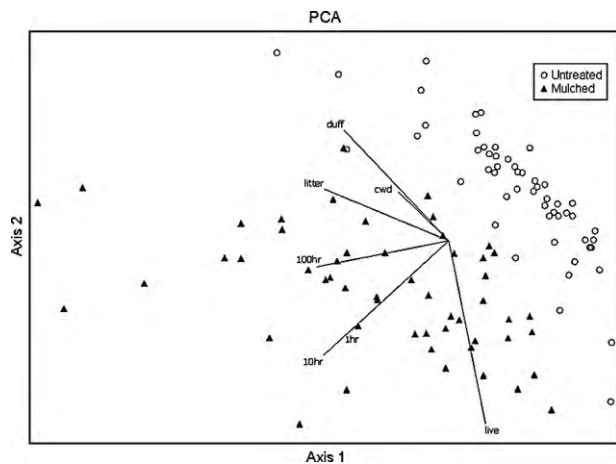


Fig. 4. Principle Components Analysis showing separation of mulched and untreated plots across all sites and forest types. Mulched plots had significantly different fuel load distributions than untreated plots ($p < 0.0001$, MRPP), with higher loads of woody fuels, litter, and live herbaceous fuels.

4. Discussion

Mulching altered stand structure and likely lowered potential active crown fire hazard in closed-canopy forest types. Mulching eliminated the majority of trees < 10 cm dbh and many overstory trees, decreasing canopy bulk density and increasing the live crown height in the lodgepole pine, mixed conifer, and ponderosa pine stands. In pinyon pine/juniper stands, mulching reduced tree density, but had little effect on canopy bulk density or canopy base height. Tree density and canopy bulk density are inherently low in the majority of pinyon pine/juniper stands and would likely resist active crown fire and be prone to passive crown fire behavior due to its large gaps between trees (Evans, 1988), and low canopy base height. In addition, a recent Ips (*Ips pini*) outbreak in many of the pinyon pine/juniper stands created a large number of standing dead trees without needles, further decreasing the potential for crown fires.

The next step in our analysis would be to assess how active and passive crown fire risk changed with the mulching treatments, but modeling these types of fire behavior is problematic in these treat-

ments. Currently available methods for modeling crown fire require the user to choose a surface fire behavior fuel model (Anderson, 1982; Scott and Burgan, 2005) or to develop a custom fuel model based on surface fuelbed characteristics. In order for a surface fire to transition into a passive crown fire (e.g. crown fire initiation), the surface fire intensity must exceed the critical fireline intensity (Van Wagner, 1977, 1993). Once the surface fire ignites the crown, the ability for the fire to propagate through the crown is based on the actual active crown fire spread rate exceeding the threshold for active fire spread rate (Van Wagner, 1993). To calculate the actual active crown fire spread rate, the surface fire spread rate and the surface fire intensity must be calculated. These two variables are estimated from the surface fire behavior fuel models (Anderson, 1982; Scott and Burgan, 2005). Kane et al. (2009) demonstrated that timber, brush, and slash-based fuelbeds (Anderson, 1982; Scott and Burgan, 2005) commonly used to model surface fire behavior differ substantially from mulched fuelbeds in sites dominated by *Arcostaphylos* and *Ceanothus* shrubs. Our PCA analysis also indicated that mulched fuelbeds in the four forest types that we sampled also differed substantially from those found in our untreated areas. Therefore, until parameters such as fuel loads, fuelbed bulk density, surface to area volume ratios, and fuel size class distribution are incorporated into the fire behavior models and predicted fire behavior is validated with experimental burning, the ability to predict active or passive crown fire behavior is hampered.

Our results and similar findings in other western forest types (Hood and Wu, 2006; Kane et al., 2009; Reiner et al., 2009), suggest that surface fuel loadings in mulched treatment areas can be estimated from measures of fuelbed depth or fuel coverage. These alternatives to planar transect sampling, which has been shown to underestimate 1-h and 10-h fuels (Kane et al., 2009), provide managers and researchers with a more accurate estimate and easy technique to estimate total surface fuel loads. Applying the provided proportion values of each fuel size class (Table 3) associated with the mulch fuelbed equations will help with estimating fuel size distribution. Our bootstrap analysis suggested that sampling 10 1-m² plots per 50-m of transect is adequate to minimize within site variability. The ability for managers to quantify the mulch fuelbed loads will help them document the impact of treatments, how the impact changes through time as fuels decompose or burn, and to begin to relate mulch biomass to observations in fire behavior and fire effects.

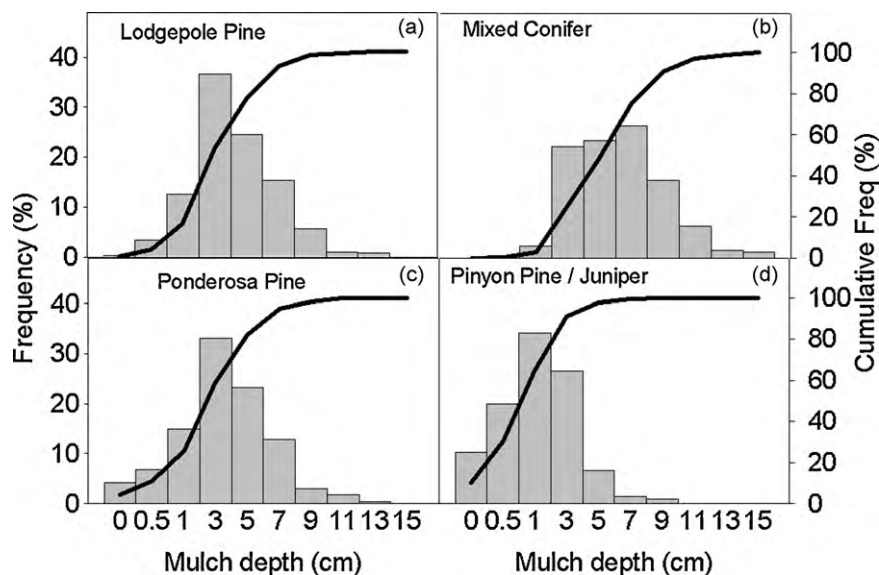


Fig. 5. Frequency (bars) and cumulative frequency (line) distribution of mulch depth (cm) at the 1 m² scale for mulched study areas in lodgepole pine, mixed conifer, ponderosa pine, and pinyon pine/juniper.

Similar to other studies (Stephens and Moghaddas, 2005; Hood and Wu, 2006; Kane et al., 2009; Reiner et al., 2009), total woody surface fuel loadings substantially increased in the mulched areas of each forest type, ranging from 27 to 63 Mg ha⁻¹. The amount of surface fuels generated by mulching was proportional to the reduction in overstory and ladder fuel density in the four forest types (mixed conifer > lodgepole pine > ponderosa pine > pinyon–juniper). Our equation that predicts total fuel loads based on the amount of tree biomass treated should help managers quantify the amount of fuels that will be generated from mulching treatments. In addition, our estimates of average mulch depth demonstrate that if all the tree biomass in the densest stands in our study was treated, the average mulch depth would range between 5.8 and 7.5 cm. Of course, the mulch depth distribution would likely have a wide range due to the variable dispersal of the woody material.

The deposition and increased continuity of the 1-h and 10-h fuels in the mulched areas created unique fuelbed characteristics that differ from untreated areas. In general, 1-h and 10-h fuels contributed the most to the total fuel load in mulched areas, a finding also reported by Kane et al. (2009). Addition of woody material to the needle litter layer resulted in a shift from a needle fuelbed or litter-twig fuelbed with typical bulk densities below 100 kg m⁻³ in untreated areas (Brown, 1981; Brown and See, 1981; van Wagendonk, 1998; Battaglia et al., 2008) to a compact woody/needle fuelbed with densities ranging between 137 and 150 kg m⁻³ in our study site as, as well as values reported for other mulched sites across the western U.S. (Busse et al., 2005; Hood and Wu, 2006; Kane et al., 2009). These compact, small particles, wood-laden fuelbeds would likely alter potential surface fire behavior and fire effects. The few studies examining the fire behavior in these mulched fuelbeds found that rate of spread and flame lengths are reduced, but flaming and smoldering duration is increased relative to untreated fuelbeds (Busse et al., 2005; Glitzenstein et al., 2006; Knapp et al., 2006; Kreye, 2008). Attempts to create custom fuel models based on measured mulch treatment fuel loads to model surface fire behavior and compare the outputs to actual observed fire behavior have been unsuccessful (Glitzenstein et al., 2006). Quantification of the mulched fuelbed characteristics in the four forest types in this study gives insight into the variables that need to be considered in the development of the new generation of fire behavior models for this fuelbed type. Furthermore, the accuracy of fire behavior prediction models which make use of such fuelbed information needs to be tested and calibrated (Cruz and Fernandes, 2008), such that uncertainty in expected fire behavior and fire effects can be accounted for in management decisions.

5. Conclusions

Agee and Skinner (2005) identified a set of principles that are important to apply in forest fuel reduction treatments to increase forest resistance to wildfire: (1) reduce surface fuels; (2) increase the height to live crown; (3) decrease crown density; and (4) retain large trees of fire-resistant species. The mulching treatments in this study achieved the last three principles. Although active crown fire risk was likely reduced in each of the forest types, the substantial increase in surface woody fuel loadings and increased continuity of woody fuel cover may lead to high-intensity surface fires that are difficult to control. The lack of appropriate tools to model potential surface and crown fire behavior for these mulched fuelbeds hinders our capability to determine appropriate management activities and fire risk factors. The broad geographic scope of this study and its replicated design across 4 forest types in Colorado has provided a characterization of surface fuel loadings in mulched areas. Commonalities among forest types were observed and should help with future planning of mulched treatments throughout the region.

Regardless of forest type, the fuelbeds created in the mulched treatments had similar bulk densities and had a high proportion of 1-h and 10-h fuel size classes. These similarities should help in the future development of new fire behavior models. The simple method of measuring fuelbed depth or cover to estimate surface fuel loads in mulched treatments should help managers to more quickly quantify the amount of fuels generated from mulching in coniferous forests of Colorado and across the western U.S.

Because mulching treatments are a relatively new management technique, information regarding treatment longevity, changes in forest microclimate, and the long-term ecological impacts is limited. Experimental burns in mulch treatments under a variety of weather conditions, including severe burning conditions, are needed to assess treatment efficacy and potential fire behavior. A case study in Idaho indicated that mulch treatments did reduce crown fire behavior and resulted in areas within the center of the treatment that had surviving trees and green vegetation (Graham et al., 2009). More observations of changes in fire behavior and subsequent effects in mulched areas subjected to wildfires are needed. Future research should focus on addressing these issues, especially since managers will continue to use mulching treatments to reduce active crown fire risk.

Acknowledgements

This research was funded by the Joint Fire Science Program (06-3-2-26). We thank Brett Wolk, Akasha Faist, Natalia Canova, and many others for their assistance with field data collection and sample processing. We send a special thanks to our cooperators at the U.S. Forest Service, Bureau of Land Management, Boulder County Open Space, Colorado State Forest Service, Colorado State Park Service, Colorado Springs Utility Company, YMCA of the Rockies, and Denver Water Board. Thanks to Laurie Porth, Rudy King, David Turner, and Scott Baggett for statistical analysis advice.

References

- Agee, J.K., Skinner, C.N., 2005. Basic principles of forest fuel reduction treatments. *Forest Ecology and Management* 211, 83–96.
- Anderson, H.E., 1982. Aids to Determining Fuel Models for Estimating Fire Behavior. Gen. Tech. Rep. INT-GTR-122. USDA Intermountain Forest and Range Experiment Station, 22 pp.
- Bate, L.J., Torgersen, T.R., Wisdom, M.J., Garton, E.O., 2004. Performance of sampling methods to estimate log characteristics for wildlife. *Forest Ecology and Management* 199, 83–102.
- Battaglia, M., Smith, F., Shepperd, W., 2008. Can prescribed fire be used to maintain fuel treatment effectiveness over time in Black Hills ponderosa pine forests? *Forest Ecology and Management* 256, 2029–2038.
- Brown, J., 1974. Handbook for Inventorying Downed Woody Material. Gen. Tech. Rep. INT-GTR-16. U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station, 24 pp.
- Brown, J.K., 1981. Bulk densities of nonuniform surface fuels and their application to fire modeling. *Forest Science* 27, 667–683.
- Brown, J.K., Oberheu, R.D., Johnston, C.M., 1982. Handbook for Inventorying Surface Fuels and Biomass in the Interior West. Gen. Tech. Rep. INT-GTR-129. U.S. Dept. of Agriculture Forest Service, Intermountain Forest and Range Experiment Station, 48 pp.
- Brown, J.K., See, T.E., 1981. Downed Dead Woody Fuel and Biomass in the Northern Rocky Mountains. Gen. Tech. Rep. INT-GTR-117. U.S. Dept. of Agriculture Forest Service, Intermountain Forest and Range Experiment Station, 48 pp.
- Busse, M.D., Fiddler, G.O., Shestak, C.J., Powers, R.F., 2005. Lethal soil temperatures during burning of masticated forest residues. *International Journal of Wildland Fire* 14, 267–276.
- Cruz, M., Fernandes, P., 2008. Development of fuel models for fire behaviour prediction in maritime pine (*Pinus pinaster* Ait.) stands. *International Journal of Wildland Fire* 17, 194–204.
- Evans, R., 1988. Management of Pinyon–Juniper Woodlands. INT-GTR-249. U.S. Department of Agriculture, Forest Service, Intermountain Research Station, 34 pp.
- Glitzenstein, J., Streng, D., Achtemeier, G., Naeher, L., Wade, D., 2006. Fuels and fire behavior in chipped and unchipped plots: implications for land management near the wildland/urban interface. *Forest Ecology and Management* 236, 18–29.

- Graham, R., Jain, T., Loseke, M., 2009. Fuel Treatments, Fire Suppression, and their Interactions with Wildfire and its Effects: The Warm Lake Experience During the Cascade Complex of Wildfires in Central Idaho, 2007. General Technical Report, RMRS-GTR-229. USDA Forest Service, Rocky Mountain Research Station, 36 pp.
- Gude, P., Rasker, R., van den Noort, J., 2008. Potential for future development on fire-prone lands. *Journal of Forestry* 106, 198–205.
- Harmon, M., Sexton, J., 1996. Guidelines for Measurement of Woody Detritus in Forest Ecosystems, vol. 20. U.S. Long-term ecological research (LTER) network office, University of Washington, Seattle, Washington.
- Harrod, R., Ohlson, P., Flatten, L., Peterson, D., Ottmar, R., 2009. A User's Guide to Thinning with Mastication Equipment. U.S. Department of Agriculture, Forest Service, Pacific Northwest Region, Okanogan-Wenatchee National Forest.
- Hood, S., Wu, R., 2006. Estimating fuel bed loadings in masticated areas. In: Andrews, P., Butler, B. (Eds.), *Fuels Management – How to Measure Success*. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, RMRS-P-41, Portland, OR, pp. 333–340.
- Huffman, D., Fule, P., Crouse, J., Pearson, K., 2009. A comparison of fire hazard mitigation alternatives in pinyon–juniper woodlands of Arizona. *Forest Ecology and Management* 257, 628–635.
- Kane, J., Varner, J., Knapp, E., 2009. Novel fuelbed characteristics associated with mechanical mastication treatments in northern California and south-western Oregon, USA. *International Journal of Wildland Fire* 18, 686–697.
- Knapp, E., Bussea, M., Varner, J., Skinner, C., Powers, R., 2006. Behavior and short-term effects of fire in masticated fuelbeds. In: *Third International Fire Ecology and Management Congress*, San Diego, CA.
- Kreye, J., 2008. *Moisture Dynamics and Fire Behavior in Mechanically Masticated Fuelbeds*. Masters thesis. Humboldt State University, 77 pp.
- Owen, S., Sieg, C., Gehring, C., Bowker, M., 2009. Above- and belowground responses to tree thinning depend on the treatment of tree debris. *Forest Ecology and Management* 259, 71–80.
- Radeloff, V.C., Hammer, R.B., Stewart, S.I., Fried, J.S., Holcomb, S.S., McKeefry, J.F., 2005. The wildland–urban interface in the United States. *Ecological Applications* 15, 799–805.
- Reiner, A., Vaillant, N., Fites-Kaufmann, J., Dailey, S., 2009. Mastication and prescribed fire impacts on fuels in a 25-year old ponderosa pine plantation, southern Sierra Nevada. *Forest Ecology and Management*, doi:10.1016/j.foreco.2009.07.050.
- Reinhardt, E.D., Crookston, N.L., 2003. The Fire and Fuels Extension to the Forest Vegetation Simulator. Gen. Tech. Rep. RMRS-GTR-116. USDA Forest Service, Rocky Mountain Research Station, 209 pp.
- Rummer, R.B., 2010. Tools for fuel management. In: Elliot, W.J., Miller, I.S., Audin, L. (Eds.), *Cumulative Watershed Effects of Fuel Management in Western United States*. Gen. Tech. Report, RMRS-GTR-231. U.S. Department of Agriculture, Forest Service, Fort Collins, CO, pp. 69–78.
- SAS, 2008. Version 9.2. Cary, NC.
- Scott, J.H., Burgan, R.E., 2005. Standard Fire Behavior Fuel Models: A Comprehensive Set for Use with Rothermel's Surface Fire Spread Model. Gen. Tech. Rep. RMRS-GTR-153. USDA Forest Service, Rocky Mountain Research Station, 72 pp.
- Sharik, T.L., Adair, W., Baker, F.A., Battaglia, M., Comfort, E.J., D'Amato, A.W., Delong, C., DeRose, R.J., Ducey, M.J., Harmon, M., Levy, L., Logan, J.A., O'Brien, J., Palik, B.J., Roberts, S.D., Rogers, P.C., Shinneman, D.J., Spies, T., Taylor, S.L., Woodall, C., Youngblood, A., 2010. Emerging themes in the ecology and management of North American forests. *International Journal of Forestry Research*, doi:10.1155/2010/964260.
- Sikkink, P.G., Keane, R.E., 2008. A comparison of five sampling techniques to estimate surface fuel loading in montane forests. *International Journal of Wildland Fire* 17, 363–379.
- Stephens, S.L., Moghaddas, J.J., 2005. Experimental fuel treatment impacts on forest structure, potential fire behavior, and predicted tree mortality in a California mixed conifer forest. *Forest Ecology and Management* 215, 21–36.
- Theobald, D.M., Romme, W.H., 2007. Expansion of the US wildland–urban interface. *Landscape Urban Planning* 83, 340–354.
- USDA/DOI, 2008. Healthy Forests Report: FY 2008 Accomplishments. Online [http://www.forestsandrangelands.gov/reports/documents/healthyforests/2008/healthy_forests_report_june_2008.pdf].
- Van Wagner, C.E., 1977. Conditions for the start and spread of crown fire. *Canadian Journal of Forest Research* 7, 23–24.
- Van Wagner, C.E., 1993. Prediction of crown fire behavior in two stands of jack pine. *Canadian Journal of Forest Research* 23, 442–449.
- van Wagtenonk, J.W., 1998. Fuel bed characteristics of Sierra Nevada Conifers. *Western Journal of Applied Forestry* 13, 73–84.
- Wolk, B., Rocca, M., 2009. Thinning and chipping small-diameter ponderosa pine changes understory plant communities on the Colorado Front Range. *Forest Ecology and Management* 257, 85–95.